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TECHNICAL REPORT
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AERIAL OBSERVATION OF GULF STREAM PHENOMENA VIRGINIA CAPES AREA, OCTOBER 1968-MAY 1969

OCTOBER 1970

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ABSTRACT

Thermal structure of a rectangular area, approximately 220 kilometers on a side and contiguous to the Continental Shelf northeast of Cape Hatteras was investigated by aircraft between 9 October 1968 and 16 May 1969 with the object of formulating an analysis and prediction model. Major features in the area included warm water northwest of the Gulf Stream, entrainment of Shelf Water into the Gulf Stream system, lateral displacement of the northern edge of the Gulf Stream, and a thermal gradient adjacent to the Continental Slope during winter. A simplified model of thermal structure describes interaction of observed water masses.

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FOREWORD

Description of oceanic thermal structure features, 50 to 100 kilometers in size, is a necessary initial step toward the development of detailed oceanographic analysis and prediction techniques suitable for Fleet utilization. Frequent oceanographic observations from aircraft supplemented by less-frequent observations from survey ships are used to delineate spatial and temporal variation of mesoscale features. Observed mesoscale conditions can be related to the large-scale circulation pattern in order to determine suitable thermal structure prediction techniques.

This report illustrates the variability of the ocean northeast of Cape Hatteras, presents an operational analysis model for this area, and demonstrates the importance of using rapid remote sensing devices to describe thermal structure.

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Captain, U.S. Navy
Commander

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Pencil notes by J. Chase

INTRODUCTION

Investigation of oceanographic phenomena in relatively shallow water contiguous to the Continental Shelf seaward of the Virginia Capes has frequently shown complex thermal structure inshore of the northern edge of the Gulf Stream. Eddies observed by Ichiye (1966, 1967) in August 1965 and June/July 1966 had major axes of 100 and 20 kilometers, respectively. Fisher (1969) reported a warm-water intrusion approximately 200 kilometers long in the area during September/October 1967. This feature appeared to extend northward from the Gulf Stream in the shape of an inverted "J". Thermohaline characteristics of the warm water strongly indicate Gulf Stream origin. A thermal gradient coincident with the Continental Slope between Cape Cod and Cape Hatteras (Church, 1937; Strack, 1953; and Cresswell, 1967) effectively separates Shelf Water from Slope Water. However, the aforementioned investigators disagree as to the period of maximum gradient; Church refers to it as a permanent feature, Strack as a permanent feature with strongest gradient during summer, and Cresswell as a seasonal feature limited to winter months. The presence of these features and the Gulf Stream results in rapid spatial and temporal change in thermal structure in the survey area.

A reasonably synoptic study of all phases of the life cycle (formation, maturation, and dissipation) of the above features requires a rapidly moving survey platform. Thus, an aircraft suitably equipped for oceanographic survey work was used to observe the area seaward of the Virginia Capes throughout a 1-year period, supported, when possible, by research vessels. This report presents the results of flight operations conducted between 9 October 1968 and 16 May 1969 and a simplified model of oceanic circulation in the area based on phenomena thus observed.

DATA COLLECTION

Oceanographic phenomena described in this paper are defined primarily by sea surface temperature (SST) as measured by an airborne radiation thermometer (ART). Measurements were made at an altitude of approximately 300 meters and have been corrected for environmental effects in accordance with Pickett (1966). The data were averaged over 1-minute periods and rounded to the nearest whole degree Celsius prior to plotting.

Subsurface features were examined from the aircraft with airborne expendable bathythermograph (AXBT) probes. Recent evaluation of this instrument (Bratnick, 1969) indicates a mean difference between the AXBT probe and reversing bottles of 0.06°C with a standard deviation of 0.37°C.

Navigation was conducted by Loran-A throughout the survey. Radar tracking by NASA, Wallops Island, determined navigational accuracy to be within 3.5 km 95 percent of the time based on experiments conducted seaward of Wallops Island (Athey, 1969).

Each flight was designed for optimum delineation of surface features in the surveyed area. Plans were modified during the series of flights as experience was gained. The flight plan yielding optimum results contained multiple legs normal to the Gulf Stream axis. Twelve flights were conducted during the 9-month survey with at least one flight conducted every month except March.

DATA ANALYSIS

Data analysis revealed four recurring oceanic processes affecting thermal structure in the Virginia Capes area: (1) lateral displacement of the northern edge of the Gulf Stream, (2) intrusion of cold water from the northwestern quadrant of the survey area to a position adjacent to the northern edge, (3) location of a frontal zone contiguous with the Continental Slope during winter, and (4) formation of two warm areas inshore of the northern edge, one a recurring eddy having a lifetime measured in days, the second a semipermanent eddy having a lifetime measured in months. Six flights have been chosen to illustrate these processes under varying weather and seasonal conditions. Additional data showing similar but less-defined features are given in the appendix.

The first flight chosen for discussion was made on 15 November 1968 (figure 1), three days after a violent storm moved through the area. Winds to 90 knots (45 m/sec) were recorded at Wallops Island, Virginia, during the peak of the storm. On the day of the flight, however, the weather conditions had moderated with westerly winds of 8 to 12 knots (4.1 to 6.2 m/sec) and 1-meter seas.

Major features observed during the flight are (1) a meanderlike bend of the Gulf Stream in the northeastern quadrant of the survey area, (2) an area of warm water (SST>21°C) adjacent to the Continental Shelf in the southwestern quadrant, and (3) a cold intrusion (SST<13°C) separating the two warm areas. Judging from surface temperature (>23°C) and strength of the gradient, the warm area in the northeastern quadrant appears to be a mesoscale Gulf Stream meander, but the thickness of the feature as measured by BT A (figure 1) suggests that it is only a shallow displacement of the northern edge. The warm area to the southwest is somewhat thicker (40 meters shown by BT B), but does not have the strong surface gradient associated with meanders. SST (<22°C) in the warm area is also slightly less than the SST of the Gulf Stream. The cold intrusion separating the two warm areas appears to be entrained in the Gulf Stream. BT C, taken a few kilometers east of the cold water, is representative of Slope Water during late autumn by virtue

of low SST (15.5°C) and sonic layer depth (SLD) greater than that of the adjacent warm water.

The flight of 28 January 1969 (figure 2) again shows a cold tongue (SST<13°C) intruding from the west along the edge of the Gulf Stream. A cold pocket (SST<13°C) is located seaward of the Continental Shelf. Downstream from the cold tongue, the Gulf Stream boundary became quite diffuse with a poorly defined tongue of warm water (SST>17°C) inshore of the stream. A thermal front (SST: 7° to 13°C) is located adjacent to the edge of the Continental Shelf in the western half of the survey area. This front was in evidence in less-developed form during flights on 17 and 20 December 1968 and 29 January 1969 (figures 15 through 17, appendix). BT D is typical of thermal structure immediately south of the northern edge, with Gulf Stream water (SST>22°C) in the near-surface layer underlain by a temperature inversion between 125 100 and 140 meters. BT's E, F, and G represent warm water inshore of the Gulf Stream, Slope Water within the cold pocket, and warm water overlying Slope Water near the Continental Shelf, respectively.

The most unusual feature of the 9 April survey (figure 3) is the southerly location of the Gulf Stream, particularly east of 74°W. Other features of interest are a large cold tongue (SST<11°C) intruding into the survey area from the west and the presence of warm water (>19°C) in the northeastern quadrant of the area. A strong temperature gradient is evident between the warm water and the cooler water to the west (6°C in less than 30 km). BT's H and I, dropped on opposite sides of the gradient, show the strong seasonal thermocline and shallow SLD in the warm water compared to the nearly positive gradient and relatively deep SLD in the cold water. The next two BT's (J and K) illustrate boundary and Gulf Stream water, respectively.

Major features observed during the 30 April flight (figure 4) were generally similar to those observed during the 9 April flight except for northerly displacement of the northern edge. Inclement weather prevented expansion of the flight pattern to determine if the warm areas were separated from the northern edge by a cold intrusion. BT's L, M, and N represent thermal structure in the northern edge, in the warm area, and in the cold tongue, respectively.

The final two flights of the survey were flown within a 4-day period in May, thus providing an excellent picture of short-term variation within the study area. Analysis of the flight of 12 May (figure 5) shows warm water (SST>22°C) inshore of the Gulf Stream west of 74°W. The warm area was approximately 40 meters thick (BT P). Of particular interest is a cold intrusion (SST<13°C) extending from the northwestern quadrant of the survey area to a position adjacent to the northern edge at 74°W and remaining in contact with the northern edge throughout the remainder of the study area. BT Q, dropped within this narrow band of cold water, shows this feature and underlying temperature inversions to

be about 130 meters thick. A third probe, BT R, was dropped well within the warm core of the Gulf Stream.

Four days later, on 16 May (figure 6), the area was resurveyed. Major features present on 12 May, though somewhat deformed, were easily identifiable. However, general northeastern displacement of the Gulf Stream is evident through comparison of the 22°C isotherm for each flight. Maximum temperatures recorded in the Gulf Stream and cold tongue by AXBT show no significant change within the period of observation. BT's S, T, and U show thermal structure in the cold tongue, in the Gulf Stream, and in the warm area, respectively.

DISCUSSION

Warm-Water Areas

Of the warm-water areas observed during the present survey, only two had characteristics similar to those reported previously by Ichiye (1966, 1967) and Fisher (1969). The first of these, a small intrusion of 17° water extending westward toward the shelf, was observed on 28 and 29 January. The small size and weak gradient delineating the warm area suggest that the observed feature is near extinction. The second, a warm water intrusion observed on 30 April, is distinguished by shape (inverted "J") and separation from the Gulf Stream to the south by a cold intrusion. Other warm areas observed during the flights appeared to be small waves of the northern edge rather than a closed eddy or tongue. Considerable short-term areal change occurred as shown by the twofold increase in size observed within a 4-day period in May. Thickness of the warm area, when observed by ship or aircraft, appeared to be on the order of 100 meters.

The vertical extent of the warm water and its relationship to adjacent water masses are shown in a cross section along 37°20'N (line AA', figure 6) taken by the USNS GILLISS (T-AGOR-4) during a combined air-sea survey in May 1969 (figure 7). The cross section, taken by shipboard expendable bathythermograph (SXBT) probes, transects the northern edge of the warm water and enters Slope Water before terminating just beyond the northern edge. The slope gradient and underlying temperature inversion are evident at the edge of the Continental Shelf. Surface temperatures on the shelf are comparable to those taken on other tracks during the same survey and are about 2°C greater than those in the cold intrusion. One explanation for the higher temperatures is inhibition of vertical mixing in shallow water by a strong thermocline, thus limiting heat gain from solar radiation to the surface layer. Depth of the warm water, as measured by the 20°C isotherm, is about 25 meters. Temperature of the inversion (7.5°C at 50 meters) beneath the frontal zone separating the warm water from Slope Water to the east is similar to that in the inversion impinging upon the Continental Slope, thus suggesting a similar source. The northern edge is identified by (1) abrupt temperature change (14.9 to

helf water
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21.2°C at the surface), (2) high SST east of the front (23.2°C), and (3) temperature inversion (minimum temperature = 10.2°C at 85 meters). A poorly defined cold filament (SST = 12.6°C) is located inshore of the northern edge. Complexity of this particular cross section is due, in part, to recurving of the gradient between the warm water and adjacent cold water.

A second warm area was observed in the northeastern quadrant of the survey area from January through completion of the study in May. Because this feature was of secondary importance to the study, detailed investigation was not possible. However, several differences are evident from the limited data available; namely, (1) larger size, (2) lifetime measured in months, (3) SST generally 5° or 6°C below Gulf Stream temperatures, and (4) separation from the northern edge by a cold filament. The frontal zone enclosing the warm area appears to be well-developed with temperature change and gradient across the front of 2° to 5°C and about 1°C/km, respectively. Thickness (generally less than 100 meters) gives the feature a lenticular appearance. Persistence of the system suggests that resupply occurs periodically, due perhaps to (1) downstream advection of smaller eddies or (2) convolutions in the northern edge as reported by Bratnick (1970).

Cold-Water Intrusion

A cold intrusion adjacent to the Gulf Stream was reported by Ford and Miller (1952), who tracked a narrow band of cold, low salinity water along the northern edge from Cape Hatteras approximately 150 kilometers downstream. Thickness of the cold water was approximately 40 meters. Observed T-S characteristics were such that the authors believed that the cold water could have originated only on the shelf north of Cape Hatteras rather than from upwelling along the northern edge or advection from the shelf south of Hatteras. Ford, et al. (1952) noted that the cold water was within the Gulf Stream system. In discussing the above papers, Stommel (1966) observed that:

> "...Were this filament of fresh water a permanent feature, the supply of fresh water required to maintain it would be of the order of magnitude $10^4 m^3$/sec., which could be supplied by river discharge along the coast. The very fact that such a slender filament can preserve its integrity along at least 1200 miles of the Gulf Stream is an indication that small-scale turbulent processes tending to transfer properties across the Stream in the upper layer are inconsiderable."

The cold intrusion observed during the flights suggests entrainment of Shelf Water by the Gulf Stream northeast of Cape Hatteras. Additional details of the cold intrusion are provided by data collected aboard the GILLISS in conjunction with the flights of 12 and 16 May. Minimum SST (hull-mounted thermistor) and salinity (bucket sample) ob-

served by the GILLISS in the intrusion were 11.2°C and 33.2°/oo, respectively. A plot of surface salinity (figure 8) shows excellent agreement with the temperature pattern derived from the ART flight of 12 May in that the 33.5°/oo isohaline is nearly coincident with the 13°C isotherm delineating the cold intrusion. An STD drop (point A on figure 8) near the cold filament shows a surface layer having a thickness of approximately 50 meters (figure 9). A second STD drop (point B on figure 8), taken in the Gulf Stream approximately 37 kilometers south of point A, is provided for comparative purposes. Note that below 250 meters the observed Slope Water is indistinguishable from Gulf Stream water below 440 meters on the T-S diagram.

A cold intrusion (such as that observed on 12 May) with parabolic cross section, surface width of 4 kilometers, and depth of 50 meters would require a drift of approximately 10 cm/sec to be within the criteria set by Stommel for maintenance of the cold filament. Although no current measurements were made during the present survey, measurements by Howe (1962) show that drift of 10 cm/sec is well within reason. Failure to observe the intrusion on three of the twelve flights comprising the survey is in agreement with the discontinuous nature of the cold filament. Nonobservance of either the intrusion or the filament by ART at the surface does not preclude the presence of either or both immediately below the surface.

Northern Edge Displacement

Considerable variation in the position and orientation of the Gulf Stream northern edge was observed throughout the survey. Variations appeared to be of two types: (1) relatively small, short-term displacement of the northern edge about the mean position and within the two-standard-deviation envelope of the northern edge computed by Pickett (1968) and (2) displacement of the northern edge outside Pickett's envelope. Maximum displacement of the observed features is unknown, since it is unlikely that the observations coincided with the time of maximum displacement.

Two relatively small-scale displacements are worth noting. The first of these occurred during the 3-day period between the flights of 17 and 20 December, when a 180-kilometer section of the northern edge moved as much as 40 kilometers to the northwest (figure 10). It is also of interest to note that downstream the northern edge on 20 December was east of its position on 17 December, thus suggesting clockwise rotation of this gradient.

The second relatively small-scale displacement shows a change in angular orientation of the northern edge downstream of a warm eddy located at approximately 36°00'N,74°30'W (figure 11). On 12 May 1969, the orientation of the northern edge east of 74°00'W was 079°T. Four days later, on 16 May, the orientation had changed to 048°T. The northern edge was displaced nearly 30 kilometers from its previous position at

73°00'W. Although the eddy expanded considerably in size during the observation period, little lateral displacement occurred.

The northern edge was observed outside Pickett's envelope during the flights of 3 and 9 April 1969 (figure 12), when the gradient was tracked on an easterly heading for approximately 110 kilometers from 35°05'N,74°04'W to 36°05'N,72°05'W. The northern edge on 24 March and 12 April (not shown) was located within the envelope. Thus, it can be concluded that the observed displacement, while of longer duration than the displacements discussed previously, probably occurred within a 10- to 14-day period.

Slope Gradient

A well-formed thermal gradient was observed adjacent to the Continental Slope during all flights between 15 November and 3 April. The gradient may be located farther offshore in the southern part of the study area because of entrainment of the Shelf Water by the Gulf Stream. Numerous BT sections (not shown) taken by the authors along 37°N between 73°W and 75°W indicate that the slope gradient is not evident at the surface between late June and early November, undoubtedly because of surface heating. The gradient remains in evidence below the surface layer until destroyed by autumnal overturning. The limited salinity data available show a salinity gradient coincident with the thermal gradient with salinity less than 33.5°/oo inshore and greater than 34.5°/oo offshore of the gradient. The resulting density gradient undoubtedly inhibits mass transport across the front.

MODEL

A simple model of oceanic circulation offshore of the Virginia Capes which integrates the oceanographic phenomena discussed above is shown as figure 13. While admittedly simplified, the model is designed to provide oceanographic forecasters with basic concepts of water mass circulation to supplement a limited supply of synoptic data.

The most dynamic feature of the model, of course, is movement of the Gulf Stream through the eastern part of the study area. SST near the northern edge of the Gulf Stream can be expected to be greater than 21°C throughout the year. Change in SST across the northern edge ranges from about 2°C in summer to more than 12°C in winter with gradients of about 2° and 5°C/km, respectively. Frontal gradients and SST can be affected greatly through the presence of cold filaments and warm areas. Currents are generally northeasterly, with speeds approaching 2 m/sec in the near-surface layer. Mass transport varies considerably and may, on occasion, exceed 100 x $10^6 m^3/sec$ (Warren and Volkman, 1968). A temperature inversion often occurs in a thin filament immediately to the south of the surface indication of the northern edge, forming relatively strong sound channels.

Eddies and intrusion of Gulf Stream water are frequently observed offshore of Oregon Inlet, probably as a result of (1) lateral movement of the Gulf Stream or (2) propagation of Gulf Stream meanders downstream of Cape Hatteras. The warm water is limited to the surface layer (100 meters), unlike observed large-scale Gulf Stream eddies, which may extend considerably deeper. Sea surface temperature is comparable to or slightly less than Gulf Stream temperatures with temperature change and gradients across the front generally slightly less than those across the northern edge. A well-defined northern edge may not be apparent at the surface in the presence of a warm area or eddy. Temperature inversions appear to be common immediately below the warm surface water. No information is available as to currents in eddies, but anticyclonic circulation is inferred from thermohaline relationships.

The larger, semipermanent warm area in the northeastern quadrant of the study area is characterized by maximum SST of 15° to 17°C in winter and near-Gulf Stream temperature in summer. Temperature change across the front varies from 2° to 5°C with a gradient of 1°C/km or less. Thermohaline relationships indicate a Gulf Stream origin.

Shelf Water in the western part of the study area may be expected to have an SST ranging from a minimum of about 5°C in winter to a maximum of greater than 27°C in summer. A frontal zone may be expected to separate the Shelf Water from offshore Slope Water in winter with temperature change and gradient across the front on the order of 5°C and 1°C/km, respectively. A temperature inversion impinging upon the Continental Slope (Cresswell, 1967; Fisher, 1969) marks the boundary between Shelf Water and Slope Water during summer and autumn. Entrainment of Shelf Water by the Gulf Stream occurs intermittently at a rate of about $1 \times 10^4 m^3$/sec., forming a cold filament along the northern edge. Shelf currents are generally southwesterly at speeds less than 20 cm/sec. Bumpus (1969) shows that current reversals may occur after periods of low rainfall.

Slope Water seaward of the Continental Shelf and inshore of the Gulf Stream is modified considerably through introduction of Gulf Stream water (eddies) and Shelf Water (offshore movement of temperature inversions). SST is comparable to Shelf Water during summer and is several degrees warmer than Shelf Water during winter. Pools of water of Gulf Stream origin frequently appear both as transient (eddies) and semipermanent (warm areas) features with corresponding SST. Thermal structure of Shelf Water is greatly complicated by intrusion of water from other sources but generally may be characterized by neutral or positive temperature gradients to depths exceeding 200 meters in winter and by strong negative gradients underlain by well-defined temperature inversions during summer and autumn.

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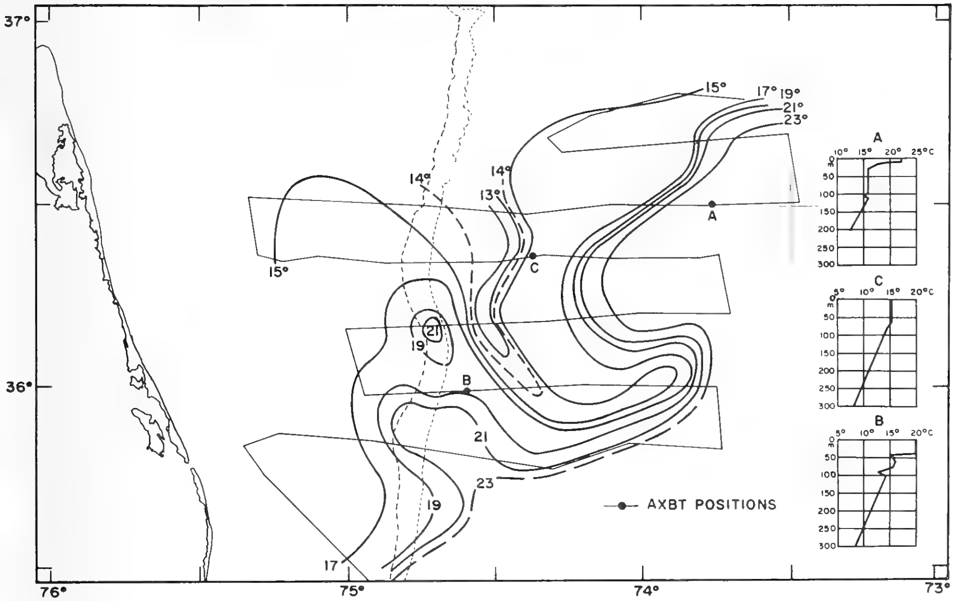

Figure 1. Surface Isotherms 15 November

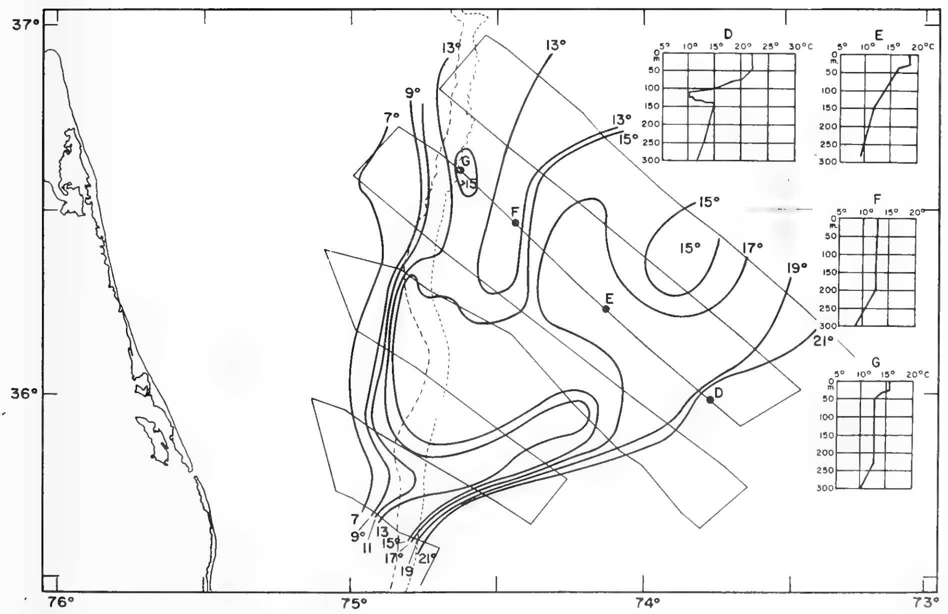

Figure 2. Surface Isotherms 28 January

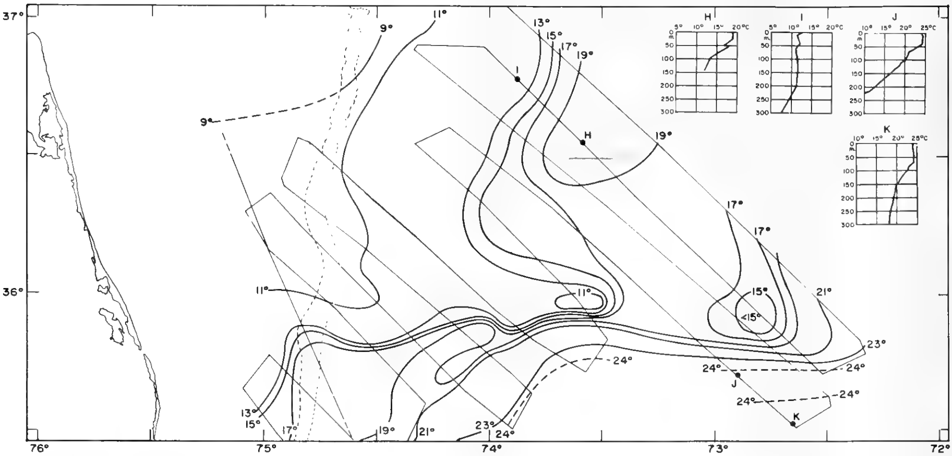

Figure 3. Surface Isotherms 9 April

Cold water ... from ...

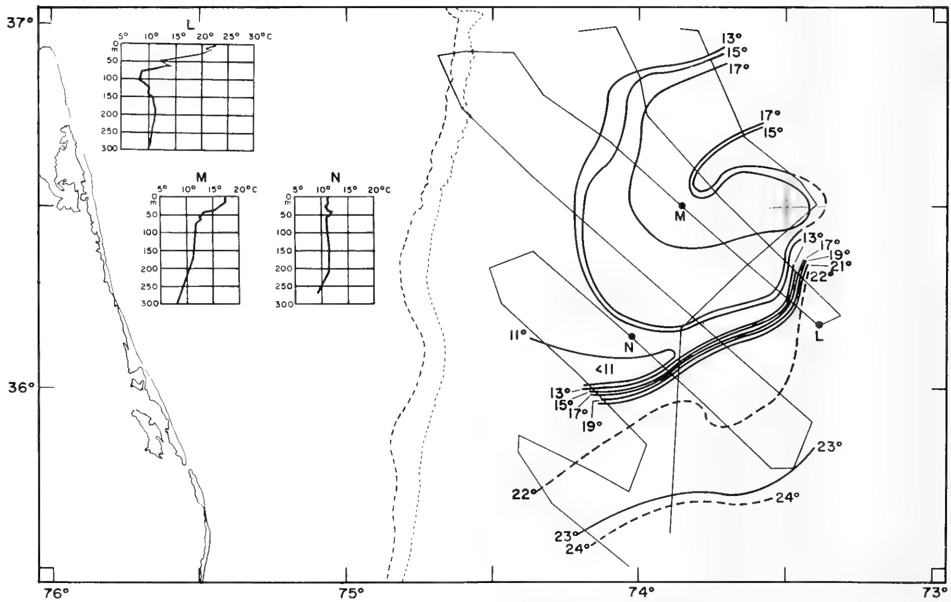

Figure 4. Surface Isotherms 30 April

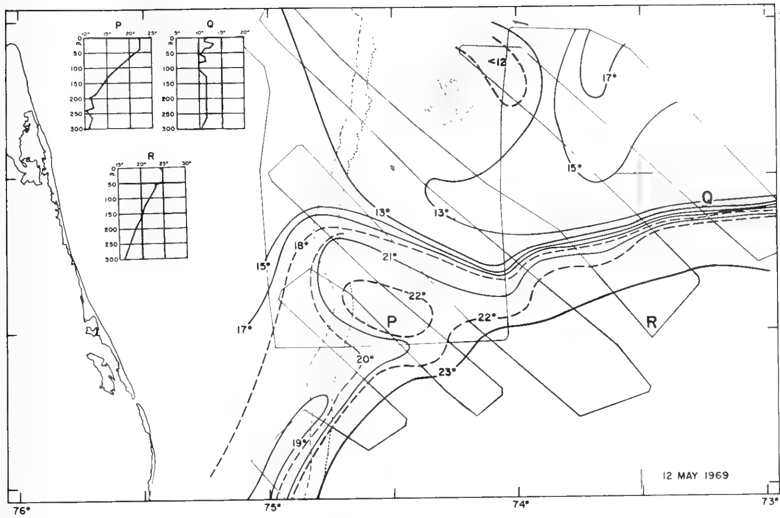

Figure 5. Surface Isotherms 12 May

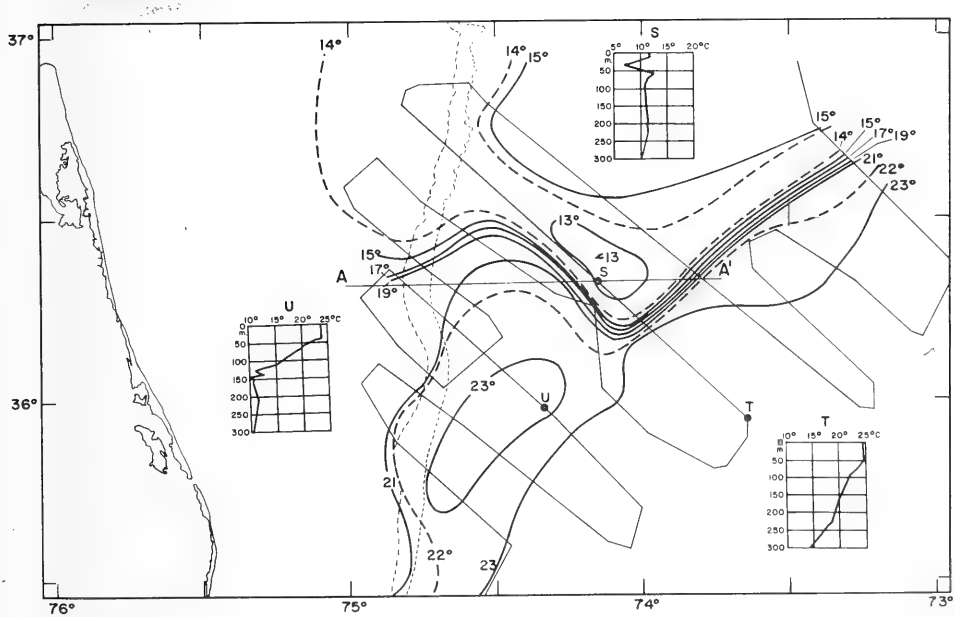

Figure 6. Surface Isotherms 16 May

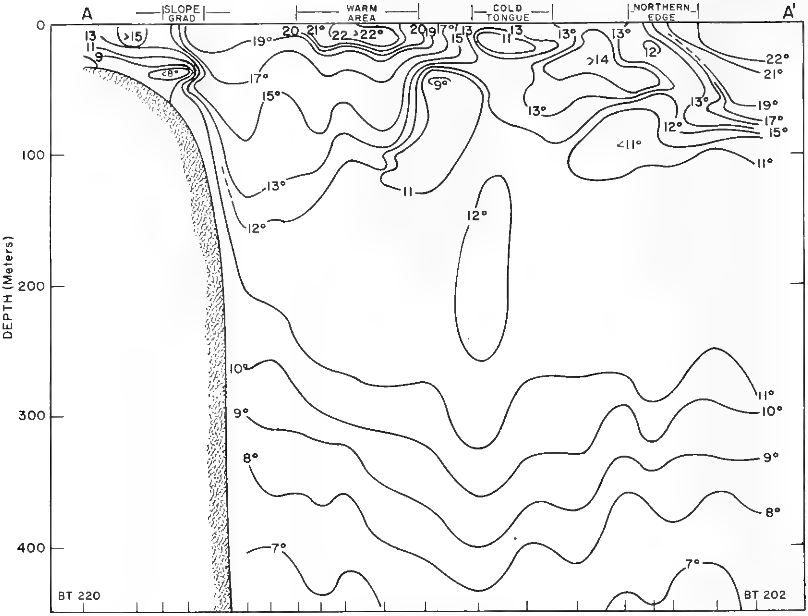

Figure 7. Temperature Section 15–16 May

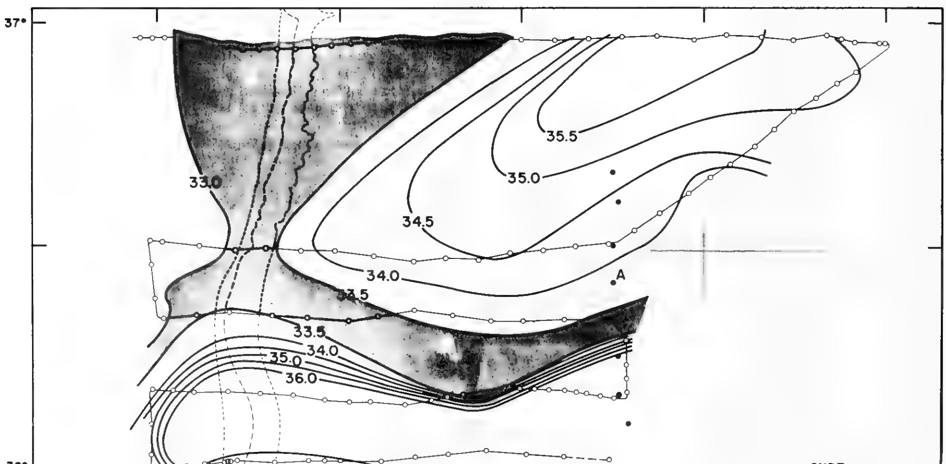

Figure 8. Surface Isohalines 11–14 May

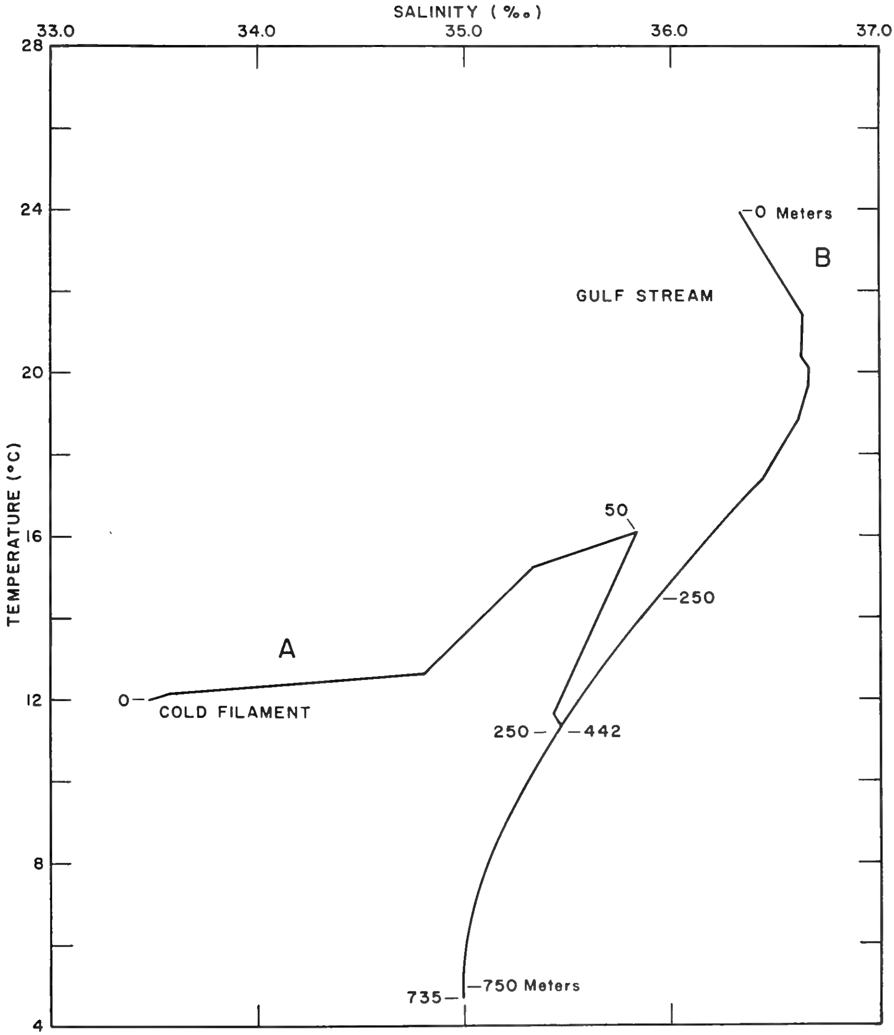

Figure 9. T-S Diagram, Northern Edge

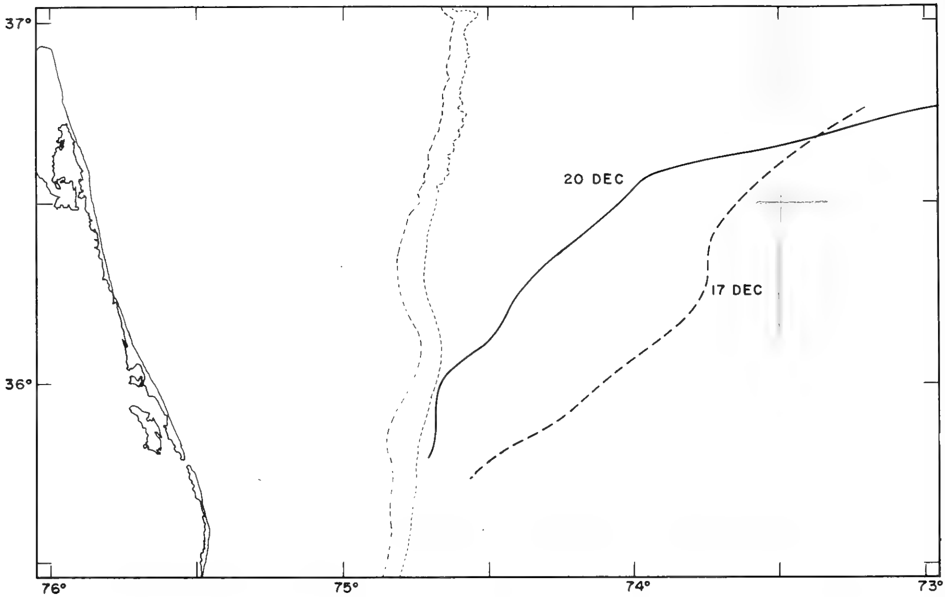

Figure 10. Lateral Displacement of Northern Edge, 17–20 December

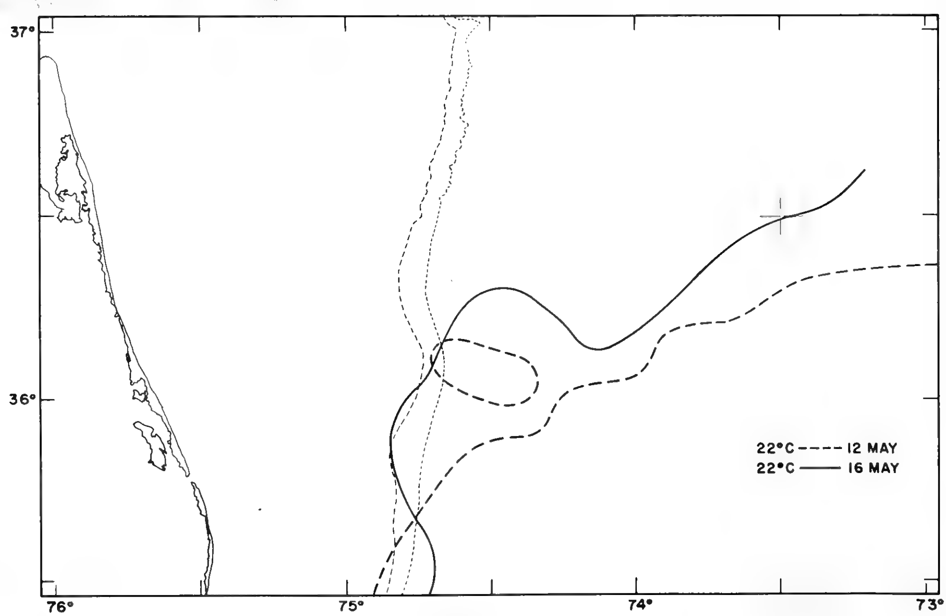

Figure 11. Lateral Displacement of Northern Edge, 12–16 May

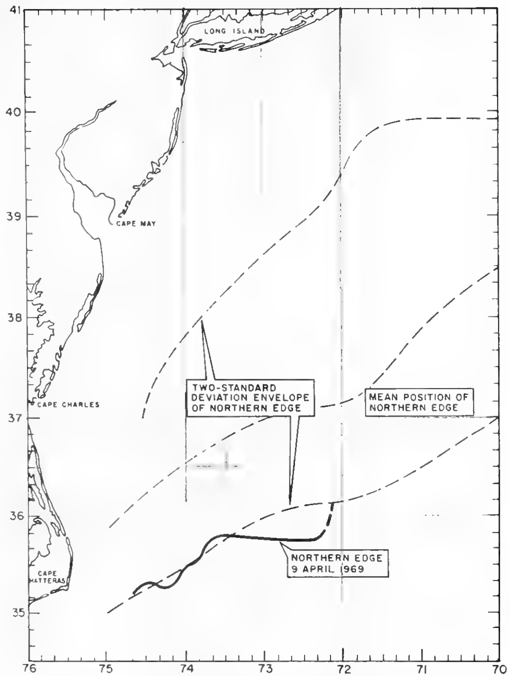

Figure 12. Lateral Displacement of Northern Edge, 9 April

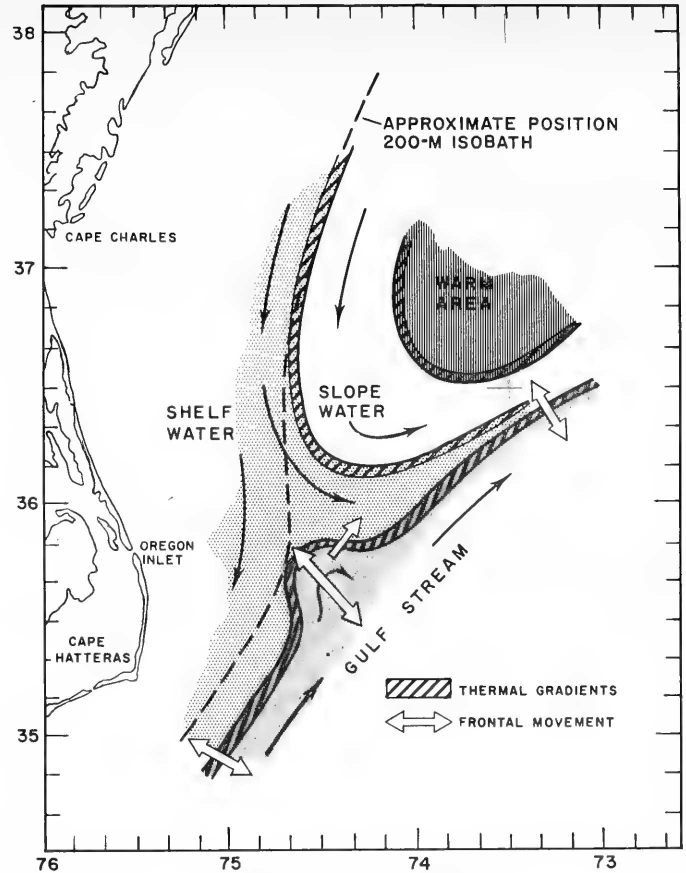

Figure 13. Thermal Structure Model

APPENDIX

SUPPLEMENTAL ANALYSES

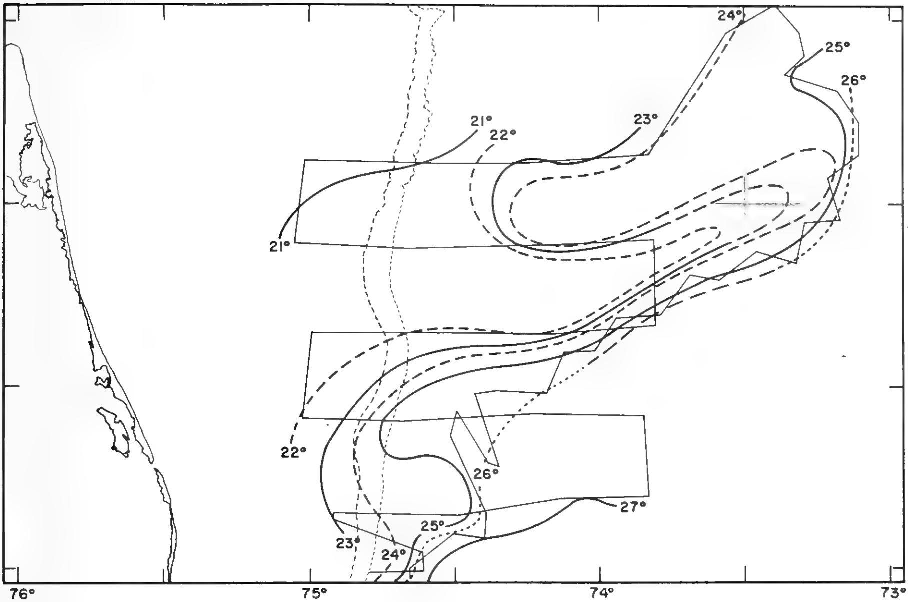

Figure 14. Surface Isotherms 9 October

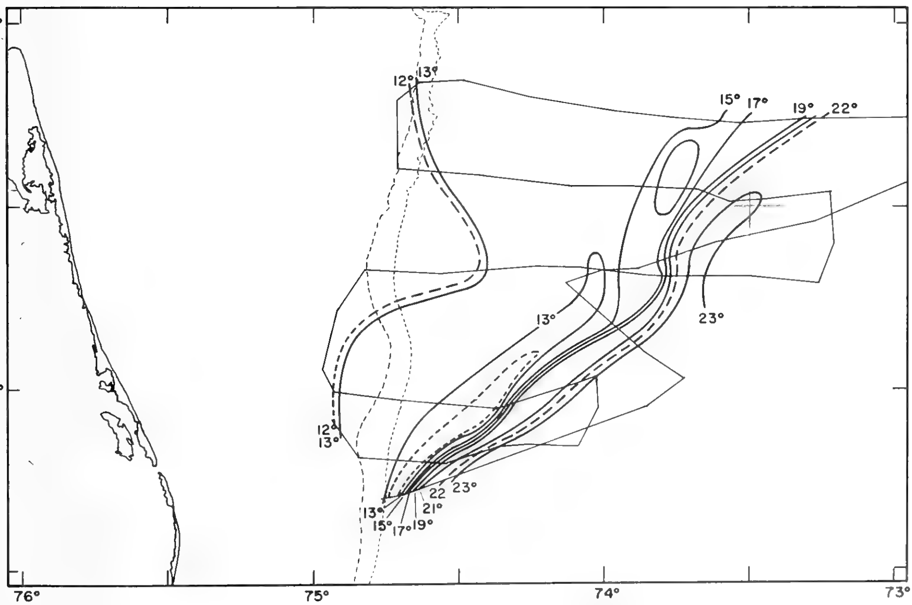

Figure 15. Surface Isotherms 17 December

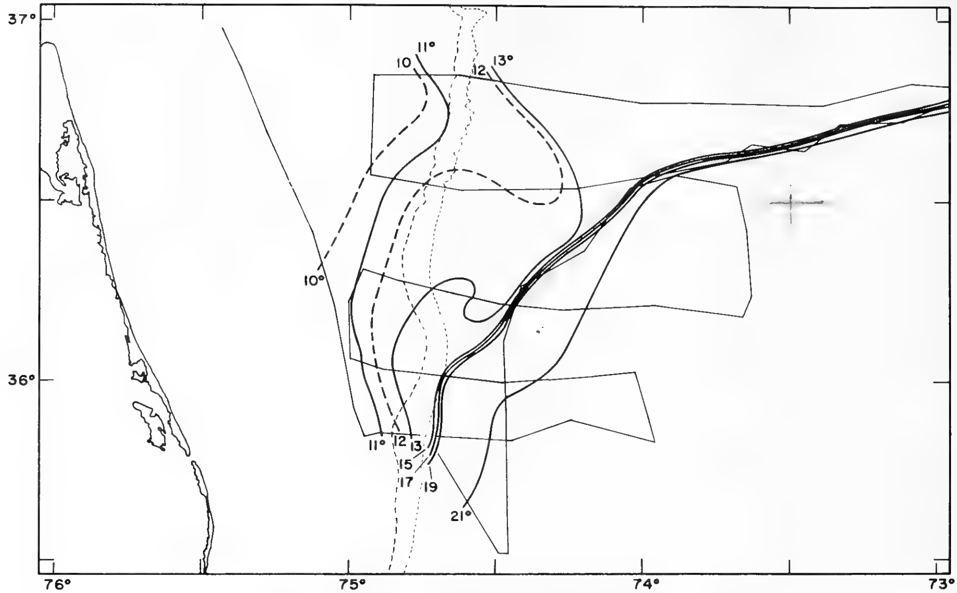

Figure 16. Surface Isotherms 20 December

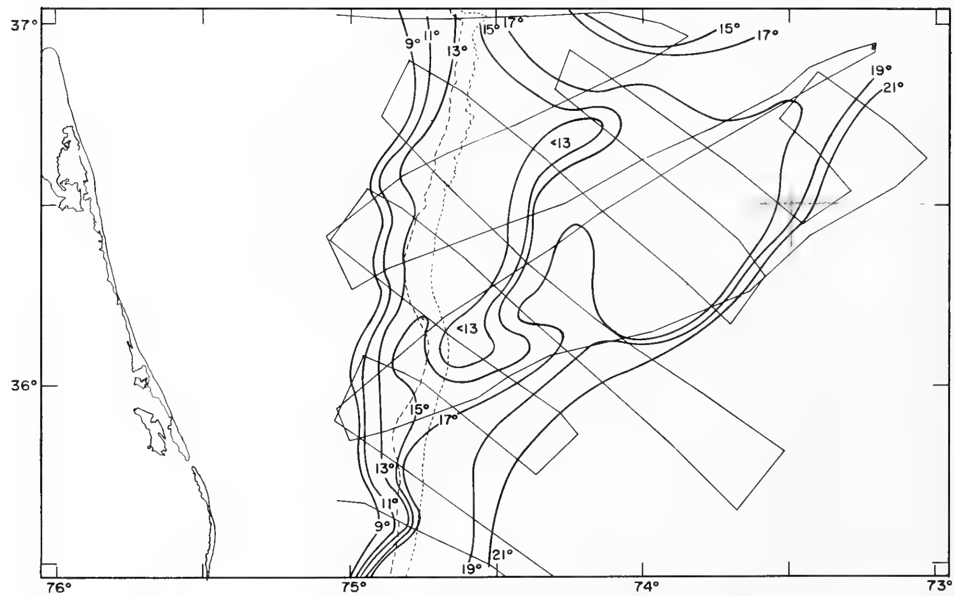

Figure 17. Surface Isotherms 29 January

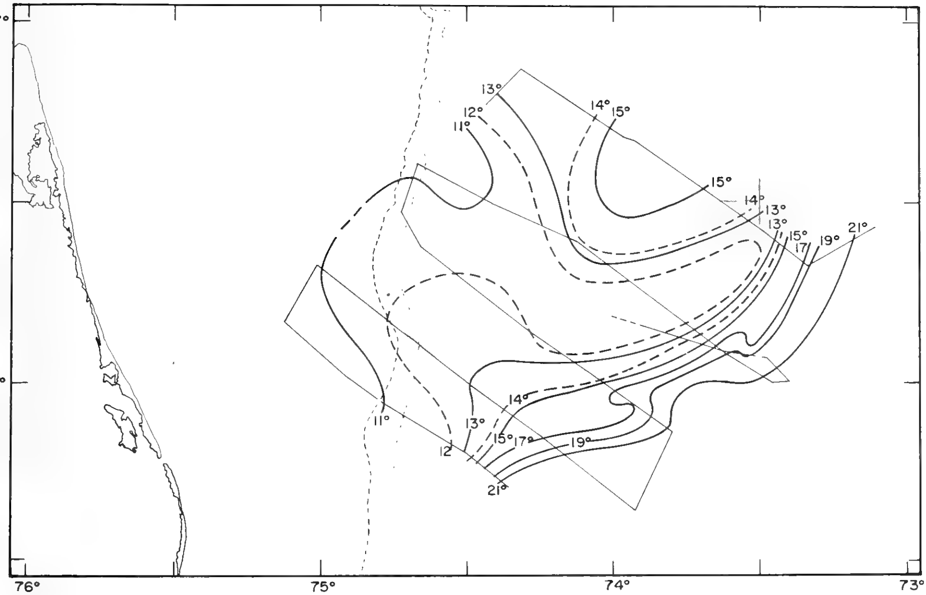

Figure 18. Surface Isotherms 7 February

westerly 4+5 lt 6th Ely 7th

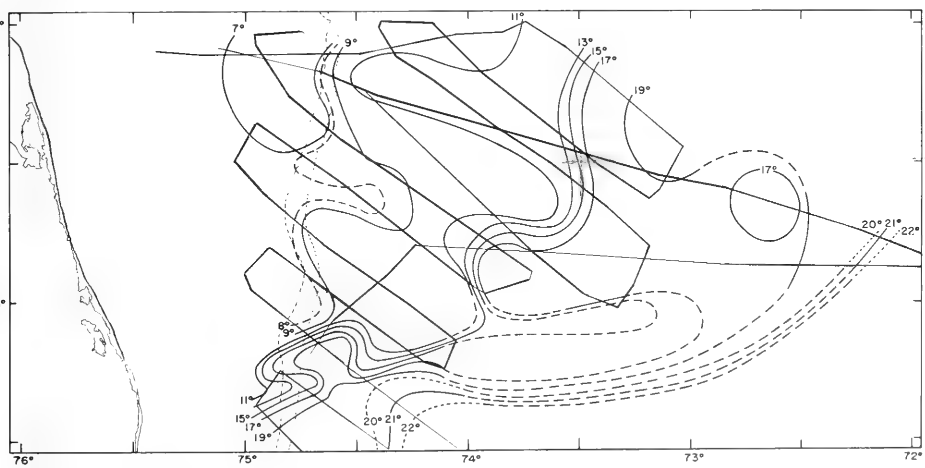

Figure 19. Surface Isotherms 3 April

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13. ABSTRACT

Thermal structure of a rectangular area, approximately 220 kilometers on a side and contiguous to the Continental Shelf northeast of Cape Hatteras was investigated by aircraft between 9 October 1968 and 16 May 1969 with the object of formulating an analysis and prediction model. Major features in the area included warm water northwest of the Gulf Stream, entrainment of Shelf Water into the Gulf Stream system, lateral displacement of the northern edge of the Gulf Stream, and a thermal gradient adjacent to the Continental Slope during winter. A simplified model of thermal structure describes interaction of observed water masses.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
CAPE HATTERAS						
CHESAPEAKE BAY						
EXPERIMENTAL DATA						
FORECASTING						
GULF STREAM						
INFRARED SENSING						
OCEANOGRAPHIC DATA						
OCEANOGRAPHIC PREDICTION						
OCEANOGRAPHY						
PHYSICAL PROPERTIES						
SALINITY						
SEA WATER						
SHALLOW WATER						
SOUND VELOCITY						
TEMPERATURE						